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Landscape characterization of Lyme disease risk using satellite imagery

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LANDSCAPE CHARACTERIZATION OF LYME DISEASE RISK USING SATELLITE IMAGERY

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ABSTRACT

LANDSCAPE CHARACTERIZATION OF LYME DISEASE RISK USING SATELLITE IMAGERY

by Sheri W. Dister

For 337 residential properties in two communities of Westchester County, New York, the relationship between Lyme disease exposure risk, based on density of nymphal *Ixodes scapularis* Say, and landscape composition was studied. Spectral indices from satellite (Landsat Thematic Mapper) data were used to characterize the landscape, and provided relative measures of vegetation moisture/type ("wetness"), as well as abundance ("greenness"). In this analysis, both exposure risk and landscape composition differed significantly between communities. Within a single community, high-risk properties were "greener" and "wetter" than lower-risk properties. Interpretation of the indices indicated that high-risk properties were characterized by an abundance of vegetation cover, of which a large proportion was broadleaf trees, which provide essential habitat for ticks and their hosts. Conversely, lower-risk properties contained more lawn but less vegetation overall. This study illustrated the utility of a remote sensing-based approach for efficiently identifying high-risk properties and communities in Lyme disease-endemic areas.

Acknowledgments

I would like to thank my committee members at San Jose State University: Dr. Bill Bros for helping me to focus and ask the right questions, for his insightful comments, and his patience; and, Dr. Mike Kutilek for leading me back to hypotheses, and for his support and understanding. In addition, I am deeply indebted to Mr. Byron Wood, my committee member at Ames Research Center, for providing me with the opportunity to do this research, and for his tremendous support and encouragement over the years.

I am grateful to Dr. Durland Fish at the Yale University School of Medicine and his colleagues (New York Medical College) for providing me with the field data used in this study, and for his advice and encouragement. I have also greatly appreciated the kindness and generosity of my colleagues at Ames, especially the assistance of Ms. Louisa Beck, who patiently read innumerable thesis drafts before demanding to see an outline, and, Ms. Jennifer Dungan, who always seemed willing to listen to my latest approach in this study. Lastly but mostly, I thank my husband Brian for putting up with me, easing the burden, and for always reminding me of what is important in life.

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Introduction

Lyme disease transmission in suburban residential areas has become a considerable human health issue in the northeastern United States (Falco & Fish 1988 a,b; Maupin et al. 1991, Stafford & Magnarelli 1993, Duffy et al. 1994a, Ginsberg 1994). In this region, residential development into recently reforested areas has brought an increased number of people into closer contact with zoonotic diseases. *Borrelia burgdorferi*, the bacterial agent that causes Lyme disease in humans (Burgdorfer et al. 1982), is transmitted by a tick vector, primarily *Ixodes scapularis* Say (= *dammini* Spielman, Clifford, Piesman & Corwin [cd. Oliver et al. 1993]), and both vector and disease agent are dependent upon a variety of forest-dwelling hosts (Spielman et al. 1985, Anderson 1989).

White-tailed deer (*Odocoileus virginianus*), which has become increasingly abundant throughout much of the Northeast, is the preferred host of the adult stage of this tick (Piesman et al. 1979, Wilson et al. 1985, Wilson et al. 1990). A number of smaller vertebrate species provide the required bloodmeals for the larval and nymphal stages (Carey et al. 1980, Anderson & Magnarelli 1980, Levine et al. 1985, Fish & Dowler 1989). Many of these host species, particularly the white-footed mouse (*Peromyscus leucopus*), also serve as reservoirs of *B. burgdorferi*, and thereby perpetuate infection in tick populations (Anderson et al. 1983, Levine et al. 1985).

In addition to providing the interface for Lyme disease transmission, the growing trend for residential land use in the forest landscape may promote disease incidence by concentrating populations of host species in close proximity to humans (Spielman et al. 1993, Stafford & Magnarelli 1993). The fragmentation of the forest associated with suburban sprawl tends to restrict dispersal of mammalian host populations while providing a diversity of resources that can support high densities of these species (Schultz et al. 1988, Fish & Dowler 1989). For example, extensive edge habitat and ornamental plantings provide additional, and often preferred, forage for deer (Hesselton & Hesselton 1982, Harlow 1984) and nesting sites for rodents (Adler et al. 1992, Frank et al. 1992), which attract tick-infested wildlife onto residential properties. Therefore, it is not surprising that in some Lyme-endemic areas the majority of *I. scapularis* bites are acquired peridomestically (Falco & Fish 1988a). Given these conditions, an emphasis on vector and/or host management in residential areas and preventative education of homeowners at risk is necessary to reduce disease incidence (Falco & Fish 1988b, Maupin et al. 1991, Falco & Daniels 1993, Ginsberg 1994).

Abundance of *I. scapularis* varies among residential areas, individual properties, and vegetation types within properties, which results in spatial variation in exposure risk (Falco & Fish 1988a, Maupin et al. 1991, Falco & Daniels 1993, Stafford & Magnarelli 1993). An understanding of the these patterns is critical to the objective of reducing Lyme disease transmission.

Studies focusing on the influence of vegetation structure on *I. scapularis* abundance in residential areas have shown that larvae and nymphs are found in higher densities in woodlots and wood ecotones than in herbaceous vegetation and lawns of properties (Maupin et al. 1991, Falco & Fish 1988b, Duffy et al. 1994a). The preference for wooded areas is thought to be due to the high moisture requirements of *Ixodes* ticks (Jaenson 1991, Maupin et al. 1991, Alder et al. 1992). In addition, patterns of host activity within residential areas also contribute heavily to tick distributions (Ginsberg & Ewing 1989, Maupin et al. 1991). Greater larval densities are found in areas highly frequented by deer (Wilson et al. 1995, Wilson et al. 1990). Larvae and nymphs are transported largely from the woods to other vegetation types by rodent hosts, whose preferences therefore determine tick dispersal patterns (Ginsberg & Ewing 1989, Daniels & Fish 1990, Maupin et al. 1991, White 1993). Furthermore, the juxtaposition of habitat types has been shown to influence tick distribution; for example, lawns adjacent to woodlots display higher abundance than those adjacent to other lawns (Fish & Falco 1988a, Maupin et al. 1991, Carroll et al. 1992, Duffy et al. 1994a). Similarly, high tick populations in a particular wooded area may reflect close proximity to other habitat types that provide resources necessary for important host species.

Considering the landscape dependence of the vector, hosts, and the interactions among these species, it follows that description and mapping of landscape composition in residential areas would aid in understanding the spatial patterns of the vector, and therefore exposure risk. From a practical perspective, the characterization of "high-risk" landscapes would provide the ability to predict which properties or areas should be considered for intervention and education efforts. Furthermore, knowledge of the distribution of risk would be extremely useful in developing appropriate strategies for reducing Lyme disease incidence in suburban areas (Falco & Daniels 1993, Stafford & Magnarelli 1993), while minimizing deleterious effects on natural communities (Ginsberg 1994).

Mapping of landscape features and patterns can be efficiently performed at a variety of spatial, spectral, and temporal resolutions using remote sensing data. Several aircraft and satellite-based sensors have been specifically designed for mapping vegetation cover (Lillesand & Keifer 1987). The data from these sensors provide an integrated view of the landscape, which is often not easily perceived from the ground. A number of previous studies have used satellite data to identify and map landscape elements indicative of vector habitat, mainly at a regional scale (Linthicum et al. 1987, Daniel 1990, Rogers & Randolph 1991, Hugh-Jones et al. 1992, Pope et al. 1993), and to develop models of human-vector contact risk (Beck et al. 1994). The landscape epidemiological approach (Pavlovsky 1966) illustrated by these studies is particularly appropriate for Lyme disease because the landscape features of host habitats may be remotely sensed as well. Glass et al. (1992) in Maryland and Dister et al. (1993) in New York have used high-resolution multispectral data, i.e., Landsat Thematic Mapper data, to identify land cover/ land use positively associated with Lyme disease exposure risk at the county level.

Satellite data have not been previously used to describe local variability in vector distribution or disease risk. With a spatial resolution of 28.5x28.5 meters, TM data may provide an effective means of mapping key landscape differences among individual properties, as well as residential communities, that are related to risk. Furthermore, because a TM scene covers 185x185 km, potentially high-risk areas may be efficiently identified over large regions. Satellite data can be processed to show the distribution of land cover classes or identify relative differences in vegetation composition, structure, abundance, or moisture content based on spectral ("vegetation") indices (Tucker 1979, Jackson 1983). Given the difficulty of labeling mixed cover types that have been grouped into discrete classes, the use of spectral indices to characterize relative differences in landscape composition is proposed as a more appropriate and time-effective approach for mapping Lyme disease exposure risk in residential areas.

In this study, spectral indices derived from Landsat TM data were used to describe the landscape composition of residential properties in two Lyme disease-endemic communities of Westchester County, New York. The objective was to determine whether the spatial and spectral resolution of the indices could characterize landscape variation associated with exposure risk. The hypothesis tested in this investigation was that the landscape composition of properties with high exposure risk differed from those of lower exposure risk.

Materials and Methods

Study Area. The two residential communities involved in the study, one in the village of Armonk and the other in Chappaqua, are located less than 12 km apart in northcentral Westchester County, New York. The county is characterized by an urban-to-rural gradient (McDonnell & Pickett 1990), which begins at its southern end, just north of New York City, and runs 75 km north to Putnam County. According to a land use map prepared by the Westchester County Planning Department (1990), the majority of the land in these villages is designated as either "low-density residential" or "undeveloped," and residential property sizes vary from 1011 sq. m. (0.25 acres) to 40, 470 sq. m. (10 acres). Secondary-regrowth deciduous forest dominates the undeveloped portion of the landscape and is comprised mainly of oak (*Quercus* spp.), hickory (*Carya* spp.), and maple (*Acer* spp.), with gray birch (*Betula alleghaniensis*), tulip (*Ciriodendron tulipifera*), and walnut (*Juglans* spp.).

There are no published records on the presence of *I. scapularis* in Westchester County prior to 1982. The species was found to be abundant in Armonk in 1982 (Falco 1987). In that same year, Lyme was listed as a reportable disease, and 60 cases were recorded in this suburban county (Williams et al. 1986). Since then, Westchester County has frequently reported the highest number of Lyme disease cases for any county in the U.S., often listing more than 1000 cases annually (CDC 1991, 1995).

Derivation of Risk Levels. The entomological data used in this study were provided by investigators at the Medical Entomology Laboratory (MEL) of the New York Medical College in Valhalla, New York. In 1990 as part of a previous epidemiological study of Lyme disease, *I. scapularis* abundance was estimated in woodlots, ecotone (i.e., woodedge), lawn, and ornamental vegetation on 386 residential properties in a 4x3-km area of Chappaqua and a 2.5x2-km area of Armonk (Frank & Fish unpublished data). The sampling design was based on a study conducted during the previous year, which also focused on these habitat types (Maupin et al. 1991).

Sampling areas for each property were randomly selected, and included 50 m^2 of woods, 300 m^2 of lawn, 150 m^2 of ornamental vegetation, and 100 m^2 of ecotone. However, because landscape composition varied among the properties, occasionally properties occurred with less than or none of a particular habitat type. In these instances, sampling was performed in the habitat area that was available, and the limitations were noted. Habitat vegetation and substrate were drag sampled once during the host-seeking period of the nymphal stage (i.e., late May to early August) using a 1-m^2 white corduroy cloth (Maupin et al. 1991). Field sampling focused on nymphs because this stage of *I. scapularis* is responsible for the majority of Lyme disease cases in the northeastern U.S. (Williams et al. 1986). Tick collections acquired slightly before or after the peak questing period were adjusted to remove potential time-based differences using scaling factors developed from a weekly monitored site (Frank & Fish unpublished data).

The tick abundance data were explored to develop an approach for assigning a level of Lyme disease exposure risk to each property based on tick density in a single habitat type. Exposure or "entomologic" risk is generally based on tick abundance and infection rate within a given area (Mather 1993); however, the proportion of ticks infected with *B. borrelia* was not determined in the field sampling. For the purpose of this study, tick density was considered to be the main source of local variation in exposure risk among properties. This assumption was supported by a previous study in Armonk, in which the percentage of ticks carrying the bacteria was found to be fairly high in all four habitat types (i.e., ranging from 25% for ticks in ornamental vegetation to 38% for ticks in ecotone) (Maupin et al. 1991).

A four-way frequency analysis (i.e., Log-linear analysis; Tabachnick & Fidell 1989) of nymph presence/absence in each habitat type was performed to determine which of the habitats most frequently had ticks and if tick presence in this habitat influenced occurrence in other vegetation on the property.

Then, based on tick density in this key habitat type, properties with the habitat (n=337) were categorized into three levels of exposure risk: no risk (no ticks per 50 m^2), low risk (as many as five ticks per 50 m^2), and high risk (more than five ticks per 50 m^2). Because an "acceptable low [population] level" for management of *I. scapularis* has not yet been determined (Stafford 1993a), the threshold set at five ticks was chosen to balance the number of observations between the low and high-risk groups when properties from the two communities were combined.

GIS and Image Processing. The residences involved in the field study were identified on 1990 black-and-white aerial photography (scale 1:2400) provided by the Westchester County Planning Department. Using ARC/INFO Geographic Information System (GIS) software, v. 6.1 (ESRI 1993), the location of each house was digitized and labeled to generate a GIS coverage that represented each residence as a point on a map. This point coverage was then registered to the universal transverse mercator (UTM) coordinate system. Field data were referenced to the digitized points using street addresses. A raster version of the residence locations was generated by gridding the point data to 28.5-m cells to match the pixel size of the satellite data. Each residence grid cell identified the center of a 3x3-pixel window used to quantify the landscape variables on and, in some cases, surrounding the property. Consequently, each observation was represented by the same amount of area, i.e., approximately 7310 sq. m. (nine TM pixels), regardless of actual property size.

Landsat TM data acquired over Westchester County on 20 May 1991 were used to characterize the landscape composition of the sampled properties. All processing of the satellite data was performed using Erdas IMAGINE software, v. 8.0 (1994). The data were first registered to the UTM coordinate system using control points identified on a digital road map developed by the Department of Transportation (1980) and provided by the Westchester County Planning Department. The portion of the TM scene containing the communities of Armonk and Chappaqua was then subsectioned from the registered image (Figure 1).

A tasseled cap transformation was performed on the TM subsection using coefficients developed by Crist et al. (1986). This transformation generated three spectral indices referred to as "brightness," "greenness," and "wetness" (Figure 2). Brightness is a weighted sum of all six reflective bands of the TM data; greenness is a contrast of the three visible bands with the near-infrared band; and wetness is produced by contrasting the visible and near-infrared bands with the longer-wavelength infrared bands (Crist et al. 1986). Greenness is generally considered to be a measure of the density of green vegetation, while, wetness is indicative of vegetation and soil moisture (Crist & Cicone 1984, Crist et al. 1986). Higher wetness is also caused by an increase

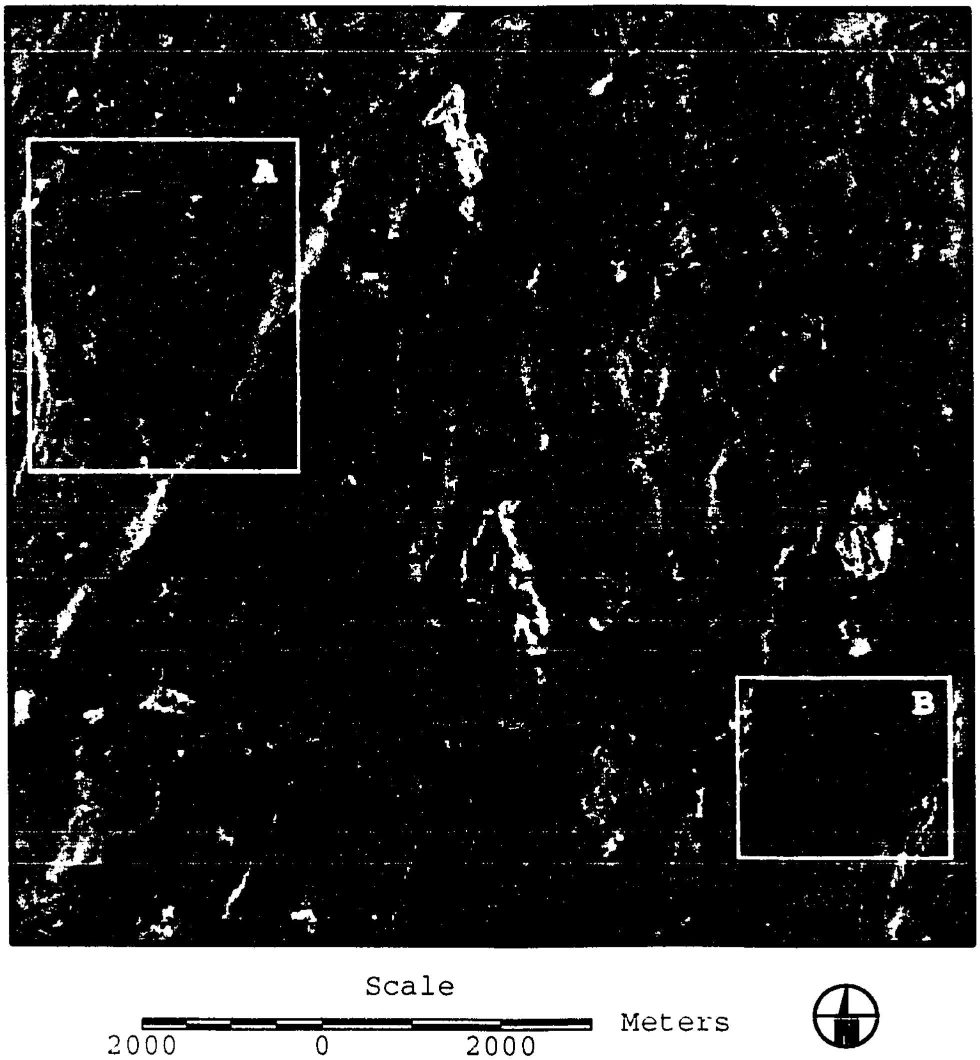

Figure 1. Color composite of Landsat TM data (bands 5, 4, and 3) for residential study sites in Westchester County, New York. A = Chappaqua; B = Armonk. Data were recorded on 20 May 1991. One pixel represents 28.5x28.5 m on the ground.

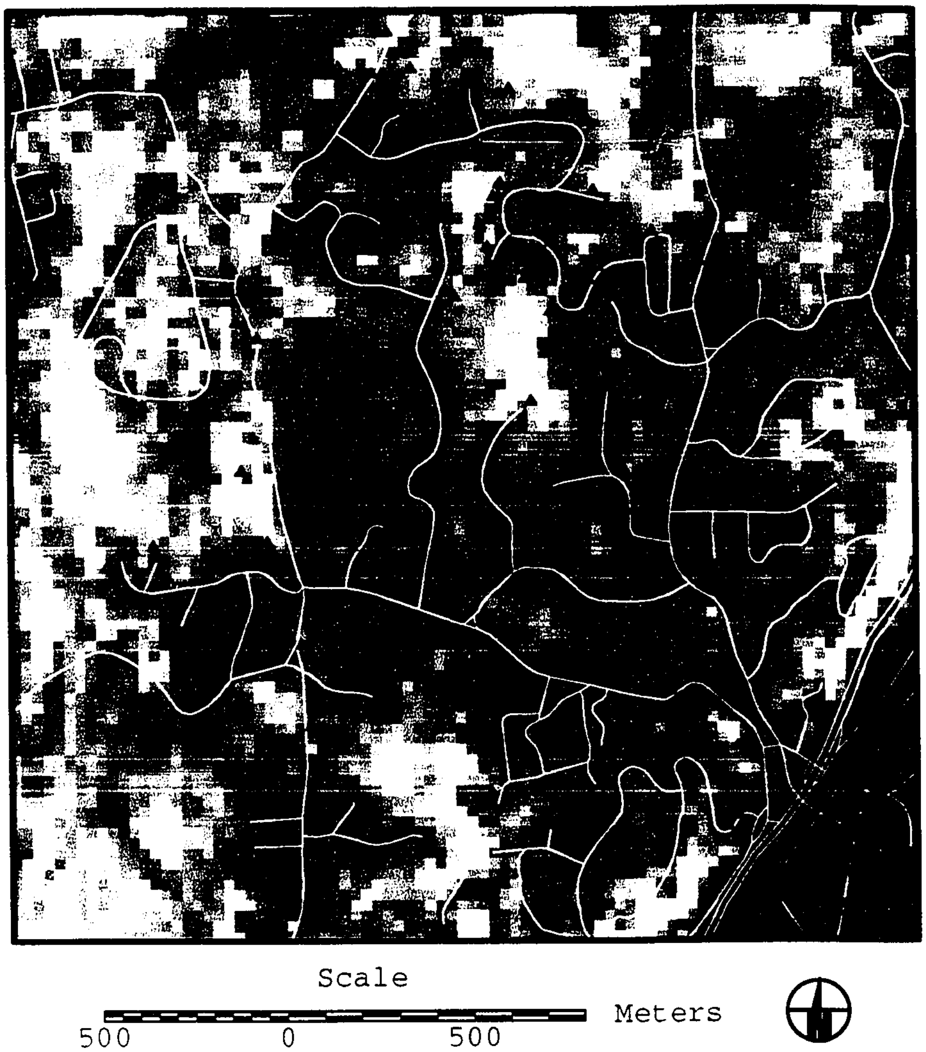

Figure 2. Wetness index derived from Landsat TM data for portion of Chappaqua. Brighter pixels are "wetter." Residential properties represented by red triangles; roads are shown in yellow.

in visible shadows, which is dependent upon the structure and density of the plant canopy. Because these characteristics differ considerably between forest and cultivated vegetation, wetness can be useful in distinguishing between such vegetation types (Crist et al. 1986). Moreover, given the high humidity requirements of *I. scapularis*, the wetness index may characterize a particularly important aspect of the environment influencing the distribution of these ticks. In general because the tasseled cap transformation uses all of visible and near-infrared reflectance information, its products may more fully characterize the variation within residential landscapes, i.e., a matrix of land cover / land use, than several more commonly known ratio indices that are based on only two data bands, such as the Normalized Difference Vegetation Index (Tucker 1979).

The topography of the properties was also quantified, in terms of elevation, slope, and aspect, to complement the vegetation description of the landscape provided by the satellite imagery. The decision to include topographic variables was also influenced by a few earlier studies, which reported an association between elevation and the coarse-scale distribution of *I. scapularis* (Schultz et al. 1984, Amersinghe et al. 1992). Topographic data of the study area were derived from Digital Elevation Models (DEMs) developed by the United States Geological Survey (1980) at a scale of 1:24,000, with 30-m horizontal resolution and 1-m vertical resolution. The 12 quadrangles comprising the majority of the county were joined, and regridded to 28.5-m size cells. A 3x3-pixel averaging filter was applied to the mosaicked data to reduce visible edge-match problems along the quadrangle sheet boundaries. The study area was then extracted from the mosaic. A terrain analysis model provided by IMAGINE was used to produce slope and aspect data layers from the composite DEM.

The six landscape variables (i.e., brightness, greenness, wetness, elevation, slope, and aspect) were quantified for 9-pixel areas, which was the size selected to describe a property. The mean and standard deviation of the spectral indices were calculated using a 3x3-pixel focal function provided by IMAGINE. Standard deviation of the indices was measured to quantify the heterogeneity in a property's landscape. In each computation, the statistics of the 9-pixel areas were stored in a new data layer. Mean elevation, slope, and aspect were also calculated for 3x3-pixel windows using the topographic data layers.

The nine data layers resulting from the focal analyses were converted to GRID v. 6.1 (ESRI 1992) files for spatial overlay with the residence locations in the GIS. The residence grid was used as a mask to identify the pixels in the landscape data layers that corresponded to the residential properties. This process extracted the 9-pixel means and standard deviations for the spectral indices and the means of the topographic variables for the properties. The resulting grids were then combined by residence location with the categorical risk variable and the data exported in ASCII format to SYSTAT, v. 5.2, (Systat 1992) for statistical analyses.

Interpretation of Spectral Indices. In order to understand the landscape variation described by the spectral indices, mean brightness, greenness, and wetness were calculated for seven land cover classes within the study area. The major cover types identified by interpretation on National High Altitude Mapping photography (NHAP 1985) were: deciduous forest, coniferous trees, managed grass (e.g., golf courses, parks, and cemeteries), urban/roads, water, open residential areas (predominantly lawn), and woody residential areas (predominantly broadleaf canopy). These diverse classes represented the range of values for the spectral indices within the study area. The two residential classes were selected to determine the spectral separability of low-density residential areas having distinct vegetation differences. The residential properties of Armonk and Chappaqua were considered to be either woody residential or to fall somewhere between the two residential cover classes defined. More than ten homogeneous patches of each of the seven cover types were identified on the photography, and then located on the tasseled-cap image. Means and standard deviations of the indices were calculated for each land cover class based on more than 800 pixels for each class.

Data Screening and Transformations. Landscape variables included in analyses were: mean greenness (GREEN), mean wetness (WET), standard deviation of greenness (SDGRN), standard deviation of wetness (SDWET), mean elevation (ELEV), mean SLOPE, and ASPECT, the latter of which was categorized as north or south. Aspect were converted from degrees to directional categories to represent the general microclimatic differences expected between northern and southern exposures. Mean brightness and standard deviation of brightness were excluded because variances in these measures appeared to be largely due to the reflectance of man-made materials, which were not of interest in this study. WET and SLOPE were transformed to correct for positive skewness using log(x+1). WET was negatively skewed, and was normalized by adding a constant (to eliminate negative values) and squaring this sum. Homogeneity of variances among the three risk levels were confirmed by Burr Foster Q tests (Anderson & McLean 1974).

Comparison of Communities. A set of statistical analyses was performed to determine if exposure risk was comparable, and the landscapes similar, for properties of Armonk and Chappaqua. The purpose of these tests was to investigate whether "community" would act as a confounding factor if all of the residential properties were used in testing the hypothesis that landscape composition was indicative of exposure risk.

An RxC test of independence (Sokal & Rohlf 1981) was used to identify dependence between the risk level of a property and where that property was located, i.e., Armonk or Chappaqua. Secondly, a Multivariate Analysis of Variance (MANOVA, Tabachnick & Fidell 1989) was performed to determine if Armonk (n=92) and Chappaqua (n=245) differed on GREEN, WET, SDGRN, SDWET, ELEV, or SLOPE, as well as a combination of these variables. For these analyses, as well as those subsequently described, the null hypothesis was rejected if $P < 0.025$. Multivariate significance in the MANOVA tests was based on the F-statistic of Wilks' Lambda.

Landscape Composition and Risk Levels. *Single community.* Using only the properties from the community of Chappaqua (no risk = 67, low = 80, and high = 98), a MANOVA was performed to determine if the risk groups differed significantly in landscape composition. Rejection of the null hypothesis would show that landscapes varied with exposure risk by level. A single community was used in this test to avoid spurious associations due to community-based differences, which had been revealed by the analyses described above. In choosing between communities for this test, the Chappaqua dataset was selected because the frequency of observations was more equitable among the three risk groups, and the sample size was much larger than that of Armonk.

The contribution of each dependent variable to maximizing differences on the canonical "landscape composition" variable was assessed through a series of analysis of covariance tests (ANCOVA), i.e., a stepdown procedure (Tabachnick & Fidell 1989). To identify which risk levels actually differed on the remotely sensed and topographic variables, the following planned comparsions were made: (1) high-risk properties versus the other two groups combined (no risk + low), and (2) no-risk properties versus low-risk properties.

Both communities. The hypothesis given above was tested again using the observations from both Armonk and Chappaqua (no risk = 136, low = 101, and high = 100). The community in which a property was located was not included as a factor, and the results of this analysis were considered to be secondary to those of the Chappaqua-only test because properties were known to differ by community. As in the first test, a stepdown analysis was performed, and similar planned comparisons were made.

The relationship between aspect and Lyme disease exposure risk was analyzed separately using a three-way frequency (Log-linear) analysis, in which community was also included as a variable. The purpose of this comparison was to determine whether risk level was dependent upon northern or southern exposure of a property. North-facing slopes may be more suitable for *I. scapularis* ticks given their need for a moist environment.

The properties were stratified by community in this analysis to reduce the probability of Type I error given that risk level was known to depend upon community and the relationship between aspect and community unknown.

Results

Derivation of Risk Levels. Of the 386 properties involved in the field study, 337 (87%) had woods that were sampled for ticks. The frequency analysis of tick presence/absence among the different habitat types revealed that the occurence of *I. scapularis* nymphs was most common in the wooded habitat of the properties. Of the total number of properties, ticks were found in the woodlots of 181 (59%), the lawns of 63 (21%), the ornamental vegetation of 62 (20%), and the woodedges of 121 (39%) (Figure 3). A Log-linear analysis of tick presence versus absence for these four habitat types showed that ticks were more likely to be present on the ornamental (G = 33.81, df = 9, P <0.001) and ecotonal vegetation (G = 42.27, df = 9, P < 0.001) of properties where ticks were also found in the wooded habitat. Tick presence on lawns appeared to be independent of tick occurrence in the woodlots of the same properties (G = 5.34, df = 6, P > 0.025). However, there was a significant association between ticks on lawns and ornamental vegetation (G = 15.51, df = 6, P < 0.025). There were no higher order interactions. These results led to the use of the tick density estimates for the wooded habitat in assigning risk levels to the properties.

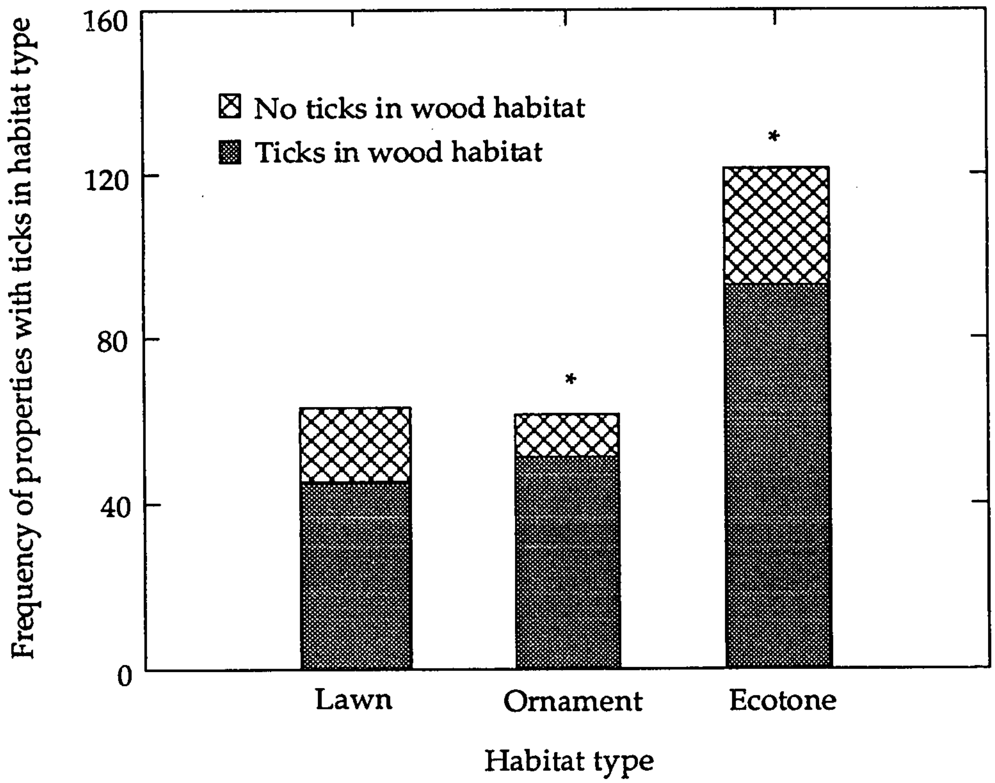

Figure 3. Effect of tick presence in wooded habitat on tick presence in other habitat types (lawn, ornamental, or ecotonal vegetation) on residential properties. $*P < 0.01$ for dependence of tick presence in habitat upon occurrence in wooded habitat.

Interpretation of Spectral Indices. Average brightness for the seven land cover classes ranged from 165.4 for managed grass to 46.9 for the water class. Urban features showed a very high standard deviation in brightness, and some of the brightest pixels were roofs and roads. Figure 4 shows how the seven classes were differentiated by mean greenness and wetness. Deciduous forest had the highest mean greenness (58.6), as well as the highest mean wetness for vegetation cover (8.7), which referred to vegetation moisture and shadowing. Managed grass had the next highest mean greenness (56.0); however, wetness was extremely low for this class (-7.8). Coniferous trees had lower greenness (36.0) than both broadleaf forest and managed grass but were much "wetter" than the grass class (5.8). Woody residential areas had both higher greenness (39.3) and wetness (6.3) than open, residential areas with large lawns (33.9 and 0.8, respectively). As expected, urban areas/roads had extremely low values for greenness (-12.0) and wetness (-13.1). The water class had the lowest greenness (-18.6) but the highest wetness (11.9).

Comparison of Communities. Of the 245 Chappaqua properties with wood habitat, 67 had no ticks, 80 were assigned low risk, and 98 high risk based on tick densities in the wooded habitat. Armonk had 69 no-risk properties, 21 low risk, and two high risk. An RxC test of independence showed that there was a significantly higher risk associated with Chappaqua properties ($G = 83.74$, df = 2, $P < 0.001$). In addition, Armonk and Chappaqua differed significantly on the canonical variable produced from the spectral

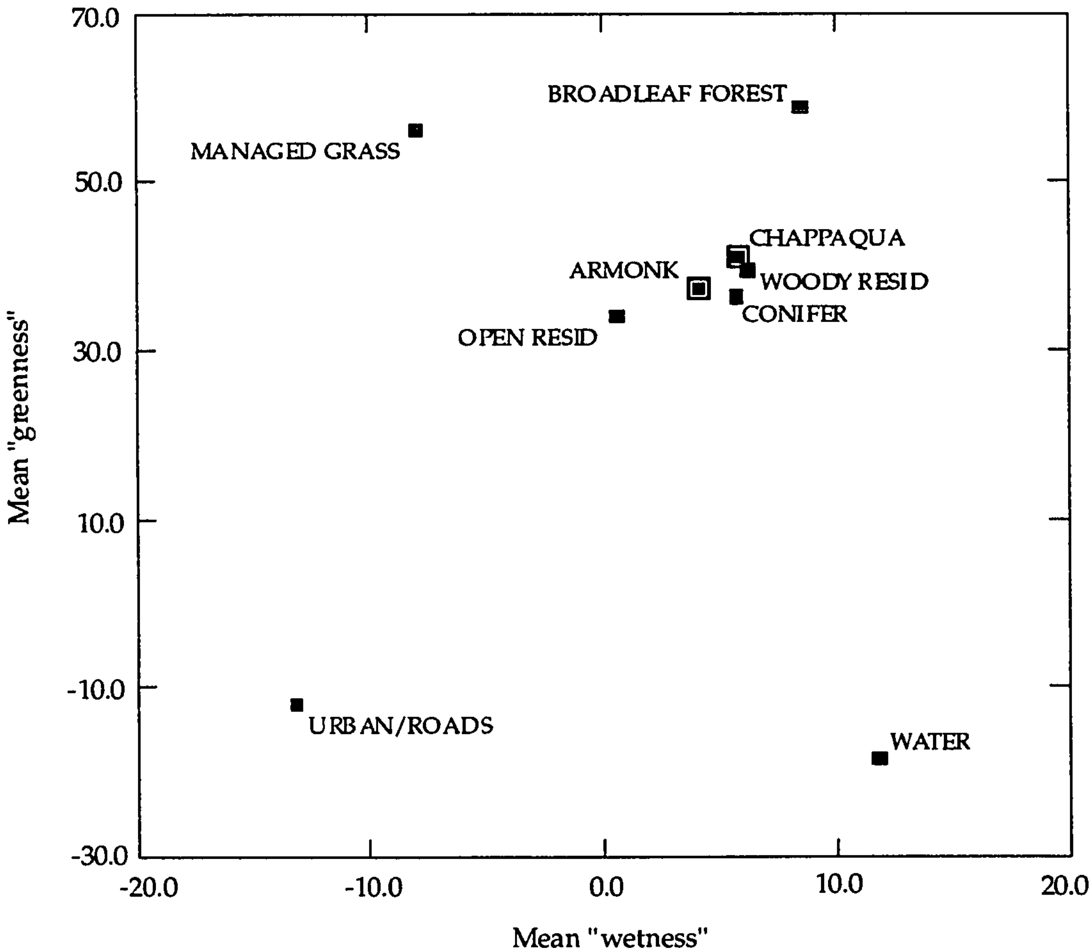

Figure 4. Mean greenness versus wetness for seven land cover classes in northcentral Westchester County. Means were computed from more than 800 pixels of each class. Also shown are means of properties in Chappaqua and Armonk.

indices and topographic variables (multivariate $F = 19.17$, df = [6,330], $P < 0.001$). Univariate significance in the test was shown by WET, SDWET, GREEN, ELEV, and SLOPE ($P < 0.01$ for SLOPE, $P < 0.001$ for all else) (Figure 5). Except for SDWET, the higher means occurred in Chappaqua. The differences in mean ELEV and SLOPE were approximately 8 meters and 3.5 degrees, respectively.

Landscape Composition and Risk Levels. *Single community.* In the omnibus MANOVA to test for landscape differences among risk levels, the high-risk group had the highest WET, GREEN, and ELEV means for the Chappaqua properties. These three variables showed significant univariate F statistics in the analysis ($P < 0.01$ for WET and ELEV, $P < 0.001$ for GREEN), and risk groups also differed significantly on a combination of all dependent variables (multivariate $F = 2.83$, df = [12, 474], $P < 0.01$). The planned comparisons revealed a difference between the high-risk group and a no-risk + low-risk group (multivariate $F = 7.19$, df = [6, 329], $P < 0.001$) (Figure 6). However, the no-risk versus low-risk means did not differ significantly on any of the landscape variables, nor on the canonical variable.

In the stepdown procedure, WET was selected for top priority, i.e., used as the first covariate to determine whether GREEN or ELEV, in this order, explained any additional variance among the three groups. The ANCOVA tests showed that neither GREEN ($F = 1.91$, df = 2, $P = 0.151$), nor ELEV

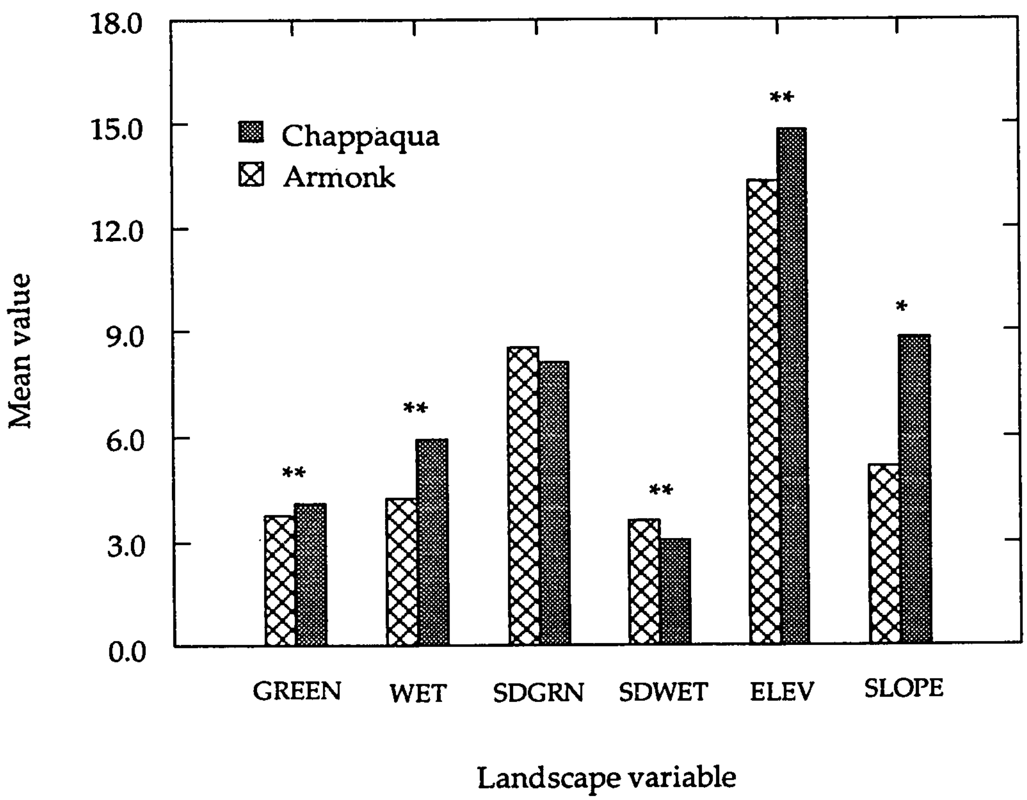

Figure 5. Comparison of landscape variable means by community (Chappaqua versus Armonk). GREEN and ELEV are divided by 10. *$P < 0.01$, **$P < 0.001$ for univariate significance.

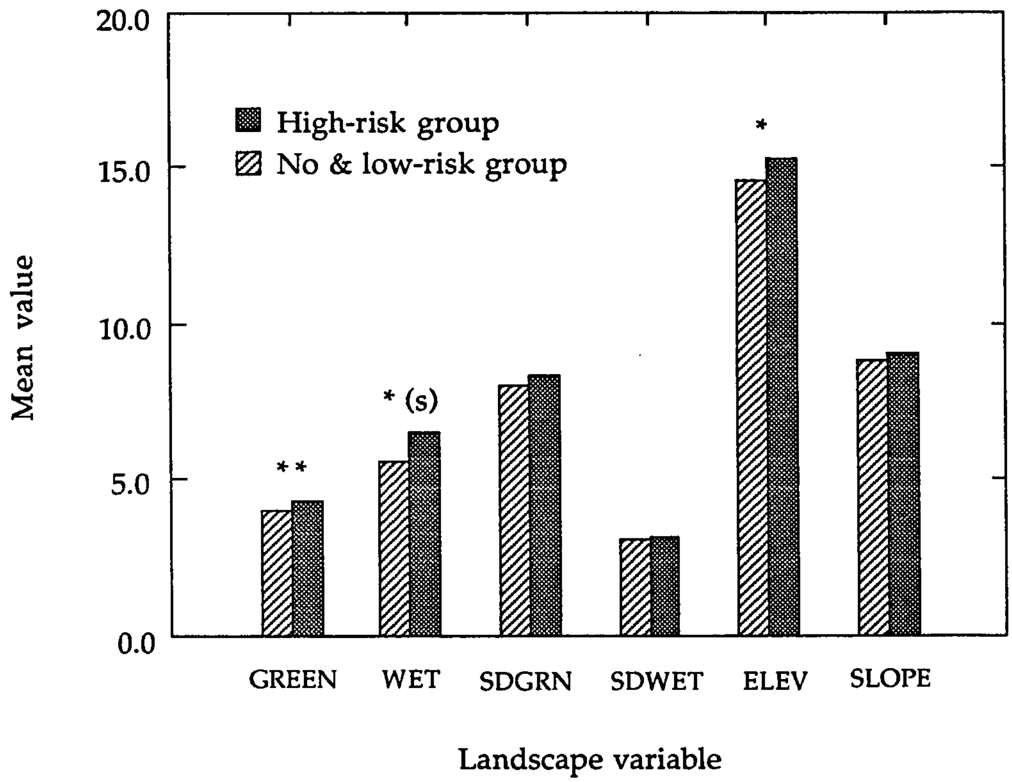

Figure 6. Comparison of landscape variable means for high-risk and no+low-risk groups in Chappaqua. GREEN and ELEV are divided by 10. $^*P < 0.01$, $^{**}P < 0.001$ for univariate significance, (s) for $P < 0.025$ in stepdown analysis.

($F = 2.94$, df = 2, $P = 0.055$) were significant covariates of WET, and therefore group differences may be explained solely by variation in WET (Figure 6).

Both communities. In the MANOVA using all of the properties, risk groups were also significantly different ($P < 0.01$) on WET, GREEN, and ELEV. SLOPE differed as well among the risk groups. For these variables, the highest means were associated with the high-risk group and the lowest means with the no-risk group. The canonical variable, which represented the combined effect of all of the landscape variables, was again significantly different among risk levels (multivariate $F = 4.47$, df = [12, 658], $P < 0.001$). Also similar to the single-community analysis, the high-risk level and the no + low-risk level were found to differ in landscape composition (multivariate $F = 7.19$, df = [6, 329], $P < 0.001$), while the no-risk versus low-risk means once again did not.

The stepdown procedure included WET, GREEN, ELEV, and SLOPE, and the contribution of a variable to the multivariate difference was tested in this order. The first ANCOVA showed that WET and GREEN were somewhat similar in explaining differences among risk groups ($F = 2.62$, df = 2, $P = 0.074$ for WET as a covariate of GREEN). However, the variance described by ELEV was shown to be significantly different ($F = 10.11$, df = 2, $P < 0.001$) from that of WET and GREEN, indicating that ELEV was a significant contributor to the multivariate when both communities were considered. SLOPE was found to be redundant with ELEV.

The Log-linear analysis of aspect, community, and risk level showed that risk level was independent of aspect ($G = 4.68$, df = 4, $P = 0.315$). In addition, aspect did not differ between Armonk and Chappaqua ($G = 4.69$, df = 5, $P = 0.455$).

Discussion

Within the urban-to-rural gradient describing Westchester County, New York (McDonnell & Pickett 1990), low-density residential developments occur in a landscape dominated by eastern deciduous forest. The setting is highly conducive to peridomestic incidences of Lyme disease (Falco & Fish 1988 a,b; Maupin et al. 1991, Ginsberg 1994). This study revealed that exposure risk for Lyme disease on residential properties was dependent upon landscape composition. Specifically, high-risk properties in the community of Chappaqua were distinguished by higher greenness and wetness values for these spectral indices derived from Landsat TM data. Thus, landscape composition in relation to exposure risk was remotely characterized in an approach that should reduce the effort required by traditional field methods for vector surveillance and disease intervention.

Comparison of greenness and wetness values for different land cover classes within the study area facilitated interpretation of the spectral data in terms of landscape characteristics that influence exposure risk. This exercise showed that areas with complete vegetation cover (i.e., broadleaf forest or managed grass) were "greener" and "wetter" than those in which vegetation and urban features occurred together, i.e., residential areas. Furthermore, the spectral indices were lowest in highly urbanized areas. Therefore, for residential properties in Chappaqua and Armonk, higher values were indicative of a greater abundance of green vegetation on a property.

In addition to abundance, vegetation composition was also reflected in the indices. Greenness and wetness were shown to distinguish among particular vegetation types, and, in a few cases, the use of both indices provided better separability than the use of a single index (see Figure 4). For example, broadleaf forest and managed grass were greener than coniferous patches, but, in terms of wetness, deciduous and coniferous forest classes scored higher than managed grass. Of the two residential cover types defined, woody residential areas were both greener and wetter than housing tracts with large lawns. However, the distinction was greater for wetness because wetness represented variation in vegetation moisture and canopy structure. Therefore, wetness was considered to be a better indicator of the variation in the contribution of lawn versus woods to the vegetation cover of a property. The results from Chappaqua suggest that high-risk properties were perhaps those with a higher proportion of woods than lawn given that the indices represent an average spectral response for the property. Lower-risk properties having the lowest scores on the indices were likely to be those in which natural habitat had been greatly reduced and vegetation cover was therefore low.

While the test of risk and landscape composition focused on a single community to avoid the problem of confounding, comparison of landscape differences between Chappaqua and Armonk properties supported the conclusions reached in this test. There was variation within a community, but, in relative terms, Chappaqua and Armonk represented high and low-risk communities, respectively. On average, Armonk had significantly lower greenness and wetness values than those of Chappaqua, and provided additional landscape variation on which to interpret the spectral indices. Also, the standard deviation of wetness for a property was shown to be higher in this community than in Chappaqua. A mixture of lawn and tree canopy would produce a higher SDWET score than dense broadleaf cover. Frank & Fish (unpublished data) noted in their habitat assessment that properties of Armonk generally had smaller woodlots and more lawn area than Chappaqua, which presented a more wooded environment.

Thus, it appears that tree canopy dominated the spectral signature of the 3x3-pixel windows of high-risk properties. Having a higher proportion of woods in the analysis window, these properties probably had larger woodlots. Maupin et al. (1991) found that tick abundance was greater on properties with larger woodlots. As has been repeatedly shown, woods and woodedges provide the most suitable habitat for *I. scapularis* (Ginsberg & Ewing 1989, Maupin et al. 1991, Adler et al. 1992, and Stafford & Magnarelli 1993). Conversely, short, open grass, e.g., well-maintained lawns, are drier and may be too desiccating of an environment, particularly for juvenile ticks (Ginsberg & Ewing 1989, Adler et al. 1992, Duffy et al. 1994a). In Chappaqua and Armonk, nymphs occurred in the wooded habitat on three times as many properties as they did in lawn habitat. Furthermore, the influence of tick occurrence in the wooded habitat on tick presence in the ecotonal and ornamental vegetation of a property suggested that the woodlots were the source of these ticks.

Woods and associated ecotonal areas are important habitat for host populations of *I. scapularis* as well, and the size and spatial context of these habitats effect their use (Ostfeld et al. 1995). Potentially, larger woodlots can permit higher deer populations, which in turn can support higher tick populations (Wilson et al. 1985, Wilson et. al. 1988, Duffy et al. 1994b). The proximity of wooded habitat to browse for deer or nesting sites for rodents would also be expected to influence host use of the area.

Both directly and indirectly, the spectral indices associated the availability of these types of resources with high-risk. For example, conifers and other evergreens that are often used as ornamental plantings in residential areas can provide food and cover for white-tailed deer during the winter (Harlow

1984). Furthermore, a recent study showed that peak *I. scapularis* densities were higher in conifer-forest habitat than deciduous, perhaps due to preferential use by hosts (Lord 1995). In the land cover interpretation of the spectral indices, conifer patches displayed high mean wetness. This relationship would appropriately identify properties with conifer trees as high-risk. As for other resources, properties with vegetation beneath the trees, e.g., shaded lawns, and small non-woody habitat patches would be characterized as high risk due to the high greenness and wetness of the dominating broadleaf canopy. Conversely, large, exposed lawns or other cultivated vegetation would contribute more highly to the spectral signature of the property, consequently lowering mean wetness. In concert with these characterizations, higher tick abundance has been found in shady lawns and lawns adjacent to woods than in lawns next other lawns (Carroll et al. 1992, Stafford et al. 1993, Duffy et al. 1994a). Furthermore, Ostfeld et al. (1995) reported that mammalian hosts tend to use small patches of non-woody vegetation more than large ones, and found that tick infestations were higher in small plots of herbaceous vegetation adjacent to woods than large ones.

While no-risk and low-risk properties presumably had less wooded habitat and/or total vegetation cover than those in the high-risk group, as shown by their overall lower greenness and wetness, there were no significant differences between the two lower-risk groups. One possible explanation is that the resolution of the satellite data was not sufficient to identify critical landscape differences between these types of properties. Alternatively, it may be that the factors responsible for the presence of a few ticks are unrelated to vegetation. These ticks do not necessarily represent an established population, but may be the result of stochastic introduction, e.g., a host passing through an area. On the other hand, low tick densities may occur in suitable habitat if the area is used less frequently by hosts due to low accessibility, i.e., fencing or other habitat manipulation (Stafford 1993b, Wilson & Deblinger 1993). It is also possible that, given the clumped nature of tick populations, some of the no-risk properties were an effect of sampling error (Daniels & Fish 1990).

From a broad perspective, it is clear that other factors also contribute to the spatial patterns of tick abundance within residential areas. The wide variances in greenness and wetness within all of the risk groups suggest that this is the case. Therefore, further research will be required to develop a model of exposure risk that integrates remote sensing characterizations with other key factors to predict exposure risk.

In further parametizing a risk model, it does not appear that topographic information would improve the identification of high-risk properties within communities. In this study, neither elevation or slope made a unique contribution to maximizing landscape distinctions among risk levels for properties in Chappaqua, as these variables were redundant with wetness.

Although there were significant community-based differences (8 meters in altitude and 3.5-degrees in slope), just how the slightly higher values in Chappaqua would promote an increased exposure risk in this community is unclear. Often, associations with altitude are based on spatial dependence, in which elevation serves as an indirect measure of another factor (e.g., vegetation, temperature, or rainfall) with which topography varies. In addition, aspect did not influence risk, and the properties of both communities occurred more frequently on south-facing slopes, where the micro-environment is considered to be drier, and therefore less suitable for ticks. However, because rainfall and humidity are generally high in the Northeast, moisture variations based on aspect may not limit tick distribution. Also, because natural vegetation is often replaced with cultivated cover in residential areas, habitat may not differ by aspect.

Overall, this study illustrated the utility of a satellite remote sensing-based approach for understanding tick distribution patterns within residential areas. From an applied standpoint, the methodologies presented here may be highly useful for efficiently identifying areas of high exposure risk in Lyme-endemic communities, and in monitoring for new problem areas as they develop. Mapping of Lyme disease risk at this scale can be accomplished for large regions as a single TM scene generally covers many counties. Moreover, vegetation indices are fairly straightforward to generate given the necessary computer software and hardware. Also, with the growth of municipal applications of GIS, street address or parcel data are becoming available more frequently in digital format.

Lastly, the visualization of risk patterns provided by satellite-derived landscape maps may also assist in selecting or developing appropriate strategies for reducing disease incidence. In this endeavor, the information provided by remote sensing technology combined with GIS-based analysis may be used to minimize both environmental and economic impacts. It is important that management strategies be focused and appropriate in order to protect natural communities (Ginsberg 1994). By effectively targeting higher risk areas, resources can be directed to where they are most needed, and unnecessary control measures, such as widespread pesticide application, can be reduced.

References Cited

Adler, G. H., S. R. Telford, III, M. L. Wilson & A. Spielman. 1992. Vegetation structure influences the burden of immature *Ixodes dammini* on its main host, *Peromyscus leucopus*. Parasitology 105: 105-110.

Amersinghe, F. P., N. L. Breisch, A. F. Azad, W. F. Gimpel, M. Greco, K. Neidhardt, B. Pagac, J. Piesman, J. Sandt, T. W. Scott & K. Sweeney. 1992. Distribution, density, and Lyme disease spirochete infection in *Ixodes dammini* (Acari: Ixodidae) on white-tailed deer in Maryland. J. Med. Entomol. 29: 54-61.

Anderson, J. F. & L. A. Magnarelli. 1980. Vertebrate host relationships and distribution of ixodid ticks (Acari: Ixodidae) in Connecticut, USA. J. Med. Entomol. 17: 314-323.

Anderson, J. F., L. A. Magnarelli, W. Burgdorfer, & A. G. Barbour. 1983. Spirochetes in *Ixodes dammini* and mammals from Connecticut. Am. J. Trop. Med. Hyg. 32: 818-824.

Anderson, J. F. 1989. Ecology of Lyme disease. Conn. Med. 53: 343-346.

Anderson, V. L. & R. A. McLean. 1974. Design of experiments: a realistic approach. Marcel Dekker, Inc., NY.

Beck, L. R., M.H. Rodríguez, S. W. Dister, A. D. Rodríguez, E. Rejmánková, A. Ulloa, R. A. Meza, D. R. Roberts, J. F. Paris, M. Spanner, R. K. Washino, C. Hacker & L. J. Legters. 1994. Remote sensing as a landscape epidemiological tool to identify villages at high risk for malaria transmission. Am. J. Trop. Med. Hyg. 51: 271-280.

Burgdorfer, W., A. G. Barbour, S. F. Hayes, J. L. Benach, E. Grunwaldt & J. P. Davis. 1982. Lyme disease: A tickborne spirochetosis? Science 216: 1317-1319.

Carey, A. B., W. L. Krinsky & A. J. Main. 1980. *Ixodes dammini* (Acari: Ixodidae) and associated Ixodid ticks in south-central Connecticut, USA. J. Med. Entomol. 17: 89-99.

Carroll M. C., H. S. Ginsberg, K. E. Hyland & R. Hu. 1992. Distribution of *Ixodes dammini* (Acari: Ixodidae) in residential lawns on Prudence Island, Rhode Island. J. Med. Entomol. 29: 1052-105.

Centers for Disease Control (CDC). 1991. MMWR 40: 417-420.

Centers for Disease Control (CDC). 1995. MMWR 44: 459-462.

Crist, E. P. & R. J. Kauth. 1986. The tasseled cap de-mystified. PE&RS 52: 81-86.

Crist, E. P. & R. C. Cicone. 1984. A physically-based transformation of thematic mapper data - the TM tasseled cap. IEEE Transaction on Geoscience and Remote Sensing 22: 256-263.

Daniel, M. & J. Kolar. 1990. Using satellite data to forecast the occurrence of the common tick *Ixodes ricinus* (L.). J. Hyg. Epidemiol. Microbiol. Immunol. 34: 243-252.

Daniels, T. J. & D. Fish. 1990. Spatial distribution and dispersal of unfed *Ixodes dammini* (Acari: Ixodidae) in southern New York. Environ. Entomol. 19: 1029-1033.

Dister, S. W., L. R. Beck, B. L. Wood, R. Falco, & D. Fish. 1993. The use of GIS and remote sensing technologies in a landscape approach to the study of Lyme disease transmission risk, pp. 1149-1155. *In* Proceedings, Seventh Annual Symposium on Geographic Information Systems in Forestry, Environment and Natural Resources Management, 15-18 February 1993. Vancouver Trade and Convention Center, Vancouver, British Columbia, Canada.

Duffy, D. C., D. D. Clark, S. R. Campbell, S. Gurney, R. Perello & N. Simon. 1994a. Landscape patterns of abundance of *Ixodes scapularis* (Acari: Ixodidae) on Shelter Island, New York. J. Med. Entomol. 31: 875-879.

Duffy, D. C., S. R. Campbell, D. Clark, C. DiMotta & S. Gurney. 1994b. *Ixodes scapularis* (Acari: Ixodidae) deer tick mesoscale populations in natural areas: effects of deer, area, and location. J. Med. Entomol. 31: 152-158.

Falco, R. C. 1987. Abundance of the deer tick Ixodes dammini (Acari: Ixodidae) in a Lyme disease endemic area of southern New York State. Ph.D. dissertation, Fordham University, NY.

Falco, R. C. & D. Fish. 1988a. Prevalence of *Ixodes dammini* near the homes of Lyme disease patients in Westchester County, New York. Amer. J. Epidemiol. 127: 826-830.

1988b. Ticks parasitizing humans in a Lyme disease endemic area of southern New York State. Am. J. Epidemiol. 128: 1146-1152.

Falco, R. C. & T. J. Daniels. 1993. Forum: Management of Lyme disease, pp. 167-171. *In* H. S. Ginsberg, [eds.], Ecology and environmental management of Lyme disease. Rutgers University Press, New Brunswick, NJ.

Fish, D. & R. C. Dowler. 1989. Host associations of ticks (Acari: Ixodidae) parasitizing medium mammals in a Lyme disease endemic area of southern New York. J. Med. Entomol. 26: 200-209.

Frank, D. H., D. Fish & T. H. Daniels. 1992. Abstract, 5th International Conference on Lyme Borreliosis. Arlington, VA.

Ginsberg, H. S. & E. W. 1989. Habitat distribution of *Ixodes dammini* (Acari: Ixodidae) and Lyme disease spirochetes on Fire Island, New York. J. Med. Entomol. 26: 183-189.

Ginsberg, H. S. 1994. Lyme disease and conservation. Conserv. Biol. 8: 343-353.

Glass, G. E., J. M. Morgan, III, Dale T. Johnson, P.M. Noy, E. Isreal & B. Schwartz. 1992. Infectious disease epidemiology and GIS: a case study of Lyme disease. Geo Info Systems 2: 65-69.

Harlow, R. F. 1984. Habitat Evaluation, pp. 601-628. *In* Lowell K. Halls, [eds.], White-tailed deer ecology and management. Stackpole Books, Harrisburg, PA.

Hesselton, W. T. & R. M. Hesselton. 1982. White-tailed deer, pp. 878-901. *In* J. A. Chapman and G. Felderham, [eds.], Wild Mammals of North America. Johns Hopkins University Press, Baltimore, MD.

Hugh-Jones, M. N. Barre, G. Nelson, K. Wehnes, J. Warner, J. Garvin & G. Garris. 1992. Landsat-TM identification of *Amblyomma variegatum* (Acari: Ixodidae) habitats in Guadelupe. Remote Sens. Environ. 40: 43-55.

Jackson, R. D. 1983. Spectral indices in *n*-space. Remote Sens. Environ. 3: 409-421.

Jaenson, T. G. 1991. The epidemiology of Lyme borreliosis. Parasitology Today 7: 39-45.

Levine, J. F., M. L. Wilson & A. Spielman. 1985. Mice as reservoirs of the Lyme disease spirochete. Am. J. Trop. Med. Hyg. 34: 355-360.

Lillesand, T. M. & R. W. Kiefer. 1987. Remote Sensing and Image Interpretation, 2nd ed. John Wiley and Sons, NY.

Linthicum, K. J., C. L. Bailey, F. G. Davies & C. J. Tucker. 1987. Detection of Rift Valley fever viral activity in Kenya by satellite remote sensing imagery. Science 235: 1656-1659.

Lord, C. C. 1995. Seasonal activity of nymphal *Ixodes scapularis* (Acari: Ixodidae) in different habitats in New Jersey. J. Med. Entomol. 32: 66-70.

Mather 1993. The dynamics of spirochete transmission between ticks and vertebrates, pp. 43-60. *In* H. S. Ginsberg [eds.], Ecology and environmental management of Lyme disease. Rutgers University Press, New Brunswick, NJ.

Maupin, G. O., D. Fish, J. Zultowsky, E. G. Campos & J. Piesman. 1991. Landscape ecology of Lyme disease in a residential area of Westchester County, New York. Am. J. Epidemiology 133: 1105-1113.

McDonnell, M. J. & S. T. A. Pickett. 1990. Ecosystem structure and function along urban-rural gradients: an unexploited opportunity for ecology. Ecology 71: 1232-1237.

Oliver, J. H., Jr., M. R. Owsley, H. J. Hutcheson, A. M. James, C. S. Chen, W. S. Irby, E. M. Dotson & D. K. McLain. 1993. Conspecificity of the ticks *Ixodes scapularis* and *I. dammini* (Acari: Ixodidae). J. Med. Entomol. 30: 54-63.

Ostfeld, R. S., O. M. Cepdea, K. R. Hazler & M. C. Miller. 1995. Ecology of Lyme disease: habitat associations of ticks (*Ixodes scapularis*) in a rural landscape. Ecol. Apps. 5: 353-361.

Pavlovsky, E. V. 1966. Natural nidality of transmissible disease. University of Illinois Press, Urbana, IL.

Piesman, J. & A. Spielman. 1979. Host associations and seasonal abundance of immature *Ixodes dammini* in southeastern Massachusetts. Ann. Entomol. Soc. Amer. 72: 829-832.

Pope, K. O., E. J. Sheffner, K. J. Linthicum, C. L. Bailey, T. M. Logan, E. S. Kasischke, K. Birney, A. R. Njogu & C. R. Roberts. 1992. Identification of central Kenyan Rift Valley Fever virus vector habitats with Landsat TM and evaluation of their flooding status with airborne imaging radar. Remote Sens. Environ. 40: 185-196.

Rogers, D. J. & S. E. Randolph. 1991. Mortality rates and population density of tsetse flies correlated with satellite imagery. Nature 351: 739-741.

Schultz, T. L., M. F. Lakat, G. S. Bowen, W. E. Parkin & J. K. Shisler. 1984. *Ixodes dammini* (Acari: Ixodidae) and other ixodid ticks collected from white-tailed deer in New Jersey: I. Geographicl distribution and its relation to selected environmental and physical factors. J. Med. Entomol. 21: 741-749.

Schultz, T. L., W. E. Parkin & E. M. Bosler. 1988. Vector tick populations and Lyme disease, a summary of control strategies. Ann. N. Y. Acad. Sci. 539: 204-211.

Sokal, R. R., and F. J. Rohlf. 1981. Biometry, 2nd ed. W. H. Freeman and Company, NY.

Spielman, A., and M. L. Wilson, J. F. Levine, & J. Piesman. 1985. Ecology of *Ixodes dammini*-born human Babesiosis and Lyme disease. Ann. Rev. Entomol. 30:439-60.

Spielman, A., S. R. Telford III & J. R. Pollack. 1993. The origins and course of the present outbreak of Lyme disease, pp. 83-96. *In* H. S. Ginsberg, [eds.], Ecology and environmental management of Lyme disease. Rutgers University Press, New Brunswick, NJ.

Stafford, K. C. 1993a. Forum: Management of Lyme disease, pp. 178-181. *In* H. S. Ginsberg, [eds.], Ecology and environmental management of Lyme disease. Rutgers University Press, New Brunswick, NJ.

1993b. Reduced abundance of *Ixodes scapularis* (Acari: Ixodidae) with exclusion of deer by electric fencing. J. Med. Entomol. 30: 986-996.

Stafford, K. C. & L. A. Magnarelli. 1993. Spatial and temporal patterns of *Ixodes scapularis* (Acari: Ixodidae) in southcentral Connecticut. J. Med. Entomol. 30: 762-771.

***SYSTAT:* Statistics. 1992.** Version 5.2 ed. SYSTAT, Inc., Evanston, IL.

Tabachnick , B. G. & L. S. Fidell. 1989. Using multivariate statistics, 2nd ed. Harper Collins Publishers, Inc., New York.

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8: 127-150.

White, D. J. 1993. Lyme disease surveillance and personal protection against ticks, pp. 99-117. *In* H. S. Ginsberg, [eds.], Ecology and environmental management of Lyme disease. Rutgers University Press, New Brunswick, NJ.

Williams, C. L., A. S. Curran, A. C. Lee, & V. O. Sousa. 1986. Lyme disease: epidemiologic characteristics of an outbreak in Westchester County, New York. Am. J. Public Health 76: 62-65.

Wilson, M. L., G. H. Adler & A. Spielman. 1985. Correlation between abundance of deer and that of the deer tick, *Ixodes dammini* (Acari: Ixodidae). Ann. Entomol. Soc. Am. 78: 172-176.

Wilson, M. L., S. R. Telford III, J. Piesman & A. Spielman. 1988. Reduced abundance of immature *Ixodes dammini* ticks (Acari: Ixodidae) following elimination of deer. J. Med. Entomol. 25: 224-228.

Wilson, M. L., A. M. Ducey, T. S. Litwin, T. A. Gavin & A. Spielman. 1990. Microgeographic distribution of immature *Ixodes dammini* ticks correlated with that of deer. Med. Vet. Entomol. 4: 151-159.

Wilson, M. L. & R. D. Deblinger. 1993. Vector management to reduce the risk of Lyme disease, pp. 126-156. *In* H. S. Ginsberg, [eds.], Ecology and environmental management of Lyme disease. Rutgers University Press, New Brunswick, NJ.